ANALYSIS OF RESIDUAL ATMOSPHERIC DELAY IN THE LOW LATITUDE REGIONS USING NETWORK-BASED GPS POSITIONING

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The atmosphere in low latitude regions is of particular interest to GPS researchers because the propagation of GPS signals becomes significantly delayed compared with other regions of the world. Hence this limits GPS positioning accuracy in equatorial regions. Although the atmospheric delay can be modelled, a residual component will still remain. Reducing, or mitigating the effect of residual atmospheric delay is of great interest, and remains a challenge, especially in equatorial regions.

Analysis of relative positioning accuracy of GPS baselines has confirmed that the residual atmospheric delay is distance-dependent, even in low latitude areas. Residual ionospheric delay is the largest component in terms of both absolute magnitude and variability. However it can be largely eliminated by forming the ionosphere-free combination of measurements made on two frequencies. The residual tropospheric delay is smaller in magnitude but rather problematic due to strong spatio-temporal variations of its wet component. Introducing additional troposphere "scale factors" in the least squares estimation of relative position can reduce the effect of the residual.

In a local GPS network, the distance-dependent errors can be spatially modelled by network-based positioning. The network-based technique generates a network "correction" for user positioning. The strategy is to partition this network correction into dispersive and non-dispersive components. The latter can be smoothed in order to enhance the ionosphere-free combination, and can be of benefit to ambiguity resolution. After this step, both the dispersive and non-dispersive correction components can be used in the final positioning step. Additional investigations are conducted for stochastic modelling of network-based positioning. Based on the least squares residuals, the variance-covariance estimation technique can be adapted to static network-based positioning. Moreover, a two-step procedure can be employed to deal with the temporal correlation in the measurements.

Test results on GPS networks in low latitude and mid-latitude areas have demonstrated that the proposed network-based positioning strategy works reasonably well in resolving the ambiguities, assisting the ambiguity validation process and in computing the user's position. Furthermore, test results of stochastic modelling in various GPS networks suggests that there are improvements in validating the ambiguity resolution results and handling the temporal correlation, although the positioning result do not differ compared to using the simple stochastic model typically used in standard baseline processing.

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ABSTRACT

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DEDICATION

To

My Dearest Wife

Adenin

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AF	Ambiguity Function
AFM	Ambiguity Function Method
AR	Ambiguity Resolution
AS	Anti Spoofing
C/A-code	Coarse Acquisition code
CORS	Continuously Operating Reference Stations
DD	Double-Differenced
DGPS	Differential Global Positioning System
DoY	Day of Year
EGM96	Earth Geopotential Model 1996
EMR	Electro-Magnetic Radiation
FKP	Flächenkorrekturparameter or Area Correction Parameters
GAW	Global Atmospheric Watch
GDAS	Global Data Assimilation System
GDOP	Geometric Dilution of Precision
GEONET	GPS Earth Observation Network
GF	Geometry Free
GIM	Global Ionospheric Map
GLONASS	Global Navigation Satellite System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
IF	Ionosphere Free
IGS	International GNSS Service
ISF	Ionospheric Scale Factor
ITRF	International Terrestrial Reference Frames
LAMBDA	Least Square Ambiguity Decorrelation Adjustment
LC	Linear Combination
LCM	Linear Combination Method
LIM	Linear Interpolation Method

MASS	Malaysian Active Surveying Station
M-code	Military Code
MINQUE	Minimum Norm Quadratic Unbiased Estimation
MMS	Malaysian Meteorological Service
NCEP	National Centres for Environmental Prediction
NL	Narrow Lane
NMEA	National Marine Electronics Association
NSF	Noise Scale Factor
NWM	Numerical Weather Models
NWP	Numerical Weather Prediction
P-code	Precise Code
PLL	Phase Lock Loop
PPP	Precise Point Positioning
PPS	Precise Positioning Service
PRN	Pseudo Random Noise
QIF	Quasi Ionosphere Free
RMS	Root Mean Square
RRE	Residual Range Error
RTCM	Radio Technical Committee for Maritime
RTK	Real-Time Kinematic
RTZD	Relative Tropospheric Zenith Delay
SA	Selective Availability
SCIGN	Southern California Integrated GPS Network
SD	Single-Differenced
SIMRSN	Singapore Integrated Multiple Reference Station
SNR	Signal to Noise Ratio
SPS	Standard Positioning Service
SYDNET	Sydney Network
TEC	Total Electron Content
TECU	Total Electron Content Unit
TMRP	Tropical Meteorological Research Programme
UN	United Nations
UNSW	University of New South Wales
VCV	Variance-Covariance

VRS	Virtual Reference Station
VTEC	Vertical Total Electron Content
WADGPS	Wide Area Differential Global Positioning System
WGS84	World Geodetic System 1984
WL	Wide Lane
WMO	World Meteorological Organisation
WRT	With Relative To
ZPD	Zenith Path Delay

LIST OF SYMBOLS

F	Carrier Frequency
f_{L1}	Primary Frequency
f_{L2}	Secondary Frequency
f_0	Fundamental Frequency
λ	Carrier Wavelength
P	Code Range Observation
p	Geometric Satellite-Receiver Range
c	Speed of EMR
dt_R	Receiver Clock Error
dt^S	Satellite Clock Error
$\bar{e}$	Other Biases and Errors Contaminating the Code Range Observation
X^S	Satellite Position Vector
X_R	Receiver Position Vector
φ	Carrier Phase Observation
N	Unknown 'Integer Carrier Phase Ambiguity'
$\bar{E}$	Other Biases and Errors Contaminating the Carrier Phase Observation
L	Carrier Phase Observation
n	Refractive Index
c	Signal in a Vacuum
v	Speed in the Medium
α	Constant
N_e	Free Electron Density
f	Corresponding Frequency
dion	First order Ionosphere Path Delay
z	Zenith Angle
R_E	Radius of the Earth
h_m	Height of the Ionosphere Layer
A	Signal Azimuth at the Receiver Location
P	Partial Pressure

T	Absolute Temperature in Kelvin
T'	Absolute Temperature in Celcius
p	Density
R	Universal Gas Constant
M	Molar Weight
dtrop	Tropospheric Delay
H'	Station Height
B/δR	Correction Quantities
$\nabla\Delta$	Double-Differencing Operator
σ^2	Variance of the One-Way Carrier Phase Measurement
I	Identity Matrix
W	Weight Matrix
f	Number of Degree of Freedom
r	Number of Receivers
x_c	Coordinates of Float Solutions
δB_{ion}	Baseline Scale Error
B	Baseline Length
dh	Station Height Error
$dtrop_{rel}$	Relative Troposphere Error
i/j	Integer Numbers
β	Arbitrary Numbers
t	Epoch
θ	Elevation Angle
μ	Along-Track Component
v	Cross-Track Component
Q	Cofactor Matrix
ρ_x	Correlation Coefficient
τ	Time Lag

Chapter 1

INTRODUCTION

1.0 Low Latitude Atmosphere – Research Plan

The Area

The ‘low latitude’ region can be defined as the area between the Earth’s Tropic of Cancer (23.5°N) and Tropic of Capricorn (23.5°S), containing the Equatorial zone (see Figure 1.1). The low latitude region is also known as the equatorial region since the atmospheric conditions are similar to those of the equatorial zone – largely a region without distinctive seasons of the year. This region experiences tropical and sub-tropical climate, is in many ways unique for researchers interested in the Earth’s climate and space weather.

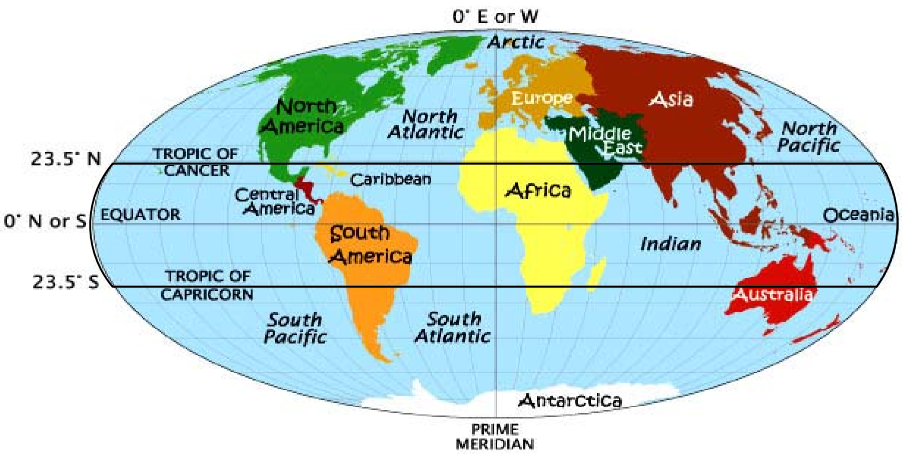

Figure 1.1 The Earth’s imaginary lines (map sourced from: http://www.worldatlas.com).

In the low latitude region the elevation angle to the Sun remains relatively high. The area is therefore exposed to intense sunlight all year round, with the temperature ranging from 20°C to 35°C (except in the desert areas). As a general rule, the warmer the air, the more water vapour it can hold. As the air rises due to temperature difference, condensation occurs and the vapour forms droplets and clouds, to ultimately produce rain. The low latitude region, especially around the Equator, therefore often gets heavy rainfall. The minimum annual precipitation is normally around 2,000mm and the relative humidity frequently exceeds 70%.

The Rationale

Abundant water and sunlight help trees produce plentiful oxygen that is vital for life on Earth. Many have claimed the tropical rainforests in low latitude region are essentially the Earth's 'lungs'. However, there is not much scientific evidence to support this claim (Broecker, 2006). Figure 1.2 shows typical scenery in the unique rainforest of Malaysia - one of the oldest tropical rainforests in the world.

Figure 1.2 Scenery of the protected Tropical Rainforest in Malaysia. **Top**: The largest (16.75 metre in diameter), the tallest (65 metre) and the oldest (1300years) 'Cengal' trees in Terengganu; **Middle**: The world's longest canopy walk (500m) located in National Rainforest Park, built 40-50 metres above the ground; **Bottom**: The 'humid' tropical rainforest in Pahang. (sourced from: http://www.forestry.gov.my and http://www.journeymalaysia.com).

The Earth's weather and climate is heavily influenced by the amount of water vapour and other greenhouse gases in the lower part of the (neutral) atmosphere known as the troposphere. An increase of temperature leads to increased evaporation. The troposphere can sustain large volumes of water vapour, which in turn traps radiant energy. This trapped radiation causes temperatures to increase and hence to create more warming. This is known as the Greenhouse Effect. (The Greenhouse Effect is a natural process of the Earth however human activity contributes to this effect as well).

In 2005, the World Meteorological Organisation and Global Atmospheric Watch (WMO-GAW), a United Nations (UN) organisation, released a report on global greenhouse gases, notably carbon dioxide (CO_2) and nitrous oxide (N_2O) (Ref: http://www.wmo.int/web/arep/gaw/ghg/ghg-bulletin-en-11-06.pdf). This report confirmed that greenhouse gases have reached new highs, with CO_2 at 379.1 parts per million (ppm) and N_2O at 319.2 parts per billion (ppb) - these values being higher than those in pre-industrial times. Moreover, WMO-GAW has indicated that from 1990 to 2005 the atmospheric radiation forced by all long-lived greenhouse gases increased by 21.5%. In fact, this is the most worrying fact for many scientists, who have debated global warming, climate changes and increased greenhouse gas emissions for over a decade (see www.davidsuzuki.org).

On the other hand, without water vapour and the other greenhouse gases planet Earth would be much colder. Since the atmosphere in the low latitude region contains large amounts of water vapour it contributes to many meteorological phenomena, such as tropical storms, and the El Niño and La Niña (in the Equatorial Pacific). Therefore serious attention has been focussed on this area. Recently the WMO has established the Tropical Meteorological Research Programme (WMO-TMRP) with the objective to improve our understanding of the physical processes of tropical systems.

In the atmosphere zone above the troposphere, the layer containing free electrons is known as the ionosphere. Here the solar radiation (predominantly ultra-violet radiation) causes ionisation. The ionosphere is important for studying the space weather which is mostly affected by solar phenomena such as solar flares, coronal holes, and coronal mass ejections which cause strong geomagnetic storms on Earth (Coster et al., 2003). The highest total electron content (TEC) values, the strongest large-scale gradients of TEC and the greatest ionospheric disturbances are typically observed at about 30° on either side of the Earth's magnetic equator (Wanninger, 1993). Figure 1.3 is a plot of the global TEC value during the latest 'solar maximum' year in 2002. In the low latitude region, the ionospheric scintillations generally occur during the period of very high solar activity, causing significant problems for radio astronomers. Ionospheric scintillations can cause unpredictable changes in the amplitude and phase of the radio signals that pass through the ionospheric layer. Even during a 'solar minimum' period, the low latitude region still has significantly larger TEC values compared to other regions.

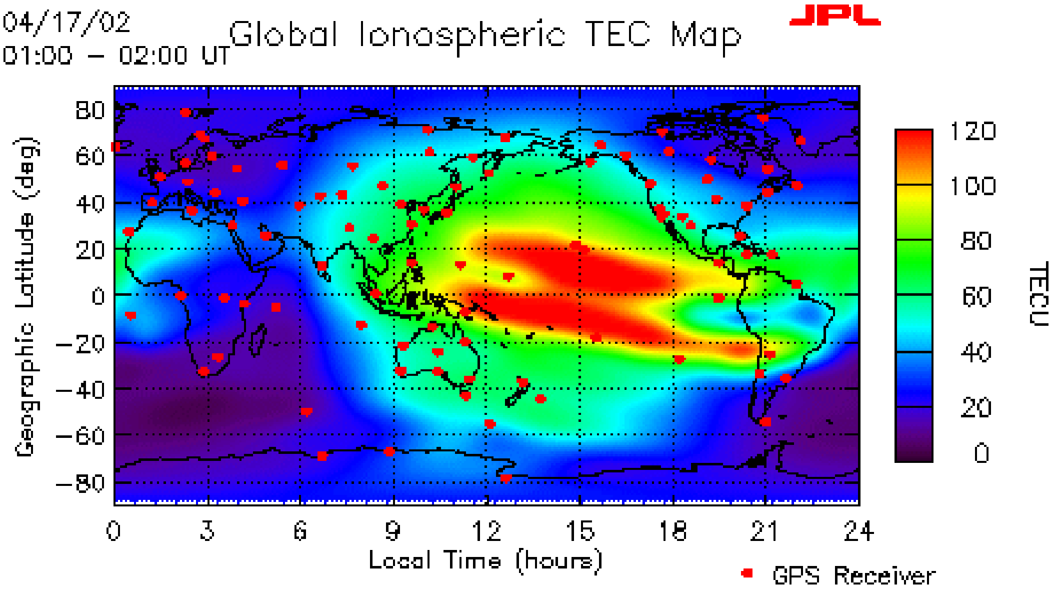

Figure 1.3 High TEC values in the low latitude region. "The Global Ionospheric Map (GIM) is generated at the Jet Propulsion Laboratory, California Institute of Technology, using GPS data collected from the global network of the International GPS Service for Geodynamics (Ref.: http://iono.jpl.nasa.gov/index.html)".

Satellite Positioning Problems

Currently, the United States Global Positioning System (GPS) is the only global satellite-based radio positioning (and timing) system with a full constellation, ensuring at least four (usually more) satellites are visible above the local horizon anywhere on Earth, at any time of the day. The satellites are used for positioning activities in static or kinematic mode, in (near) real-time or post-mission mode, to address a whole range of applications including military and security use, surveying and mapping, earth sciences, land and maritime transportation, aviation, agriculture, tsunami alert, wildlife monitoring, recreational activities, and many more. There is also a growing interest in the study of the interaction between the GPS signals and the atmosphere for Earth weather and climate and space weather research.

One of the major concerns for GPS users in the low latitude region is the effect of Earth's atmosphere on positioning. This is because of atmospheric propagation delay on the GPS signals due to the ionospheric and the tropospheric layers. In the worse case scenario, strong ionospheric scintillation can cause GPS receivers to lose lock, or receivers are not able to maintain lock for prolonged periods of time (Wanninger, 1993; Leick, 2004). Moreover, the large amount of water vapour also affects the propagation of GPS signals through the troposphere. In GPS surveying and other high accuracy positioning applications, 'double-differencing' is the preferred technique to cancel out the effect of the atmospheric delay and other spatially correlated errors. This differencing technique is less effective in low latitude areas since the *residual* atmospheric delay could complicate the positioning process.

The Challenge

Since the conditions in the atmosphere vary both spatially and temporally, it is important to analyse the quality of positioning results in many places and at different times. In low latitude regions the atmosphere is very active and still little understood from a GPS point of view. Hence understanding the complex physical and chemical processes of the Earth's atmosphere could be improved by intensive research in the low latitude region, providing a challenge for both atmospheric studies and precise positioning activities.

1.1 Motivation for Research

1.1.1 The Continuously Operating Reference Stations

Over the last decade GPS Continuously Operating Reference Stations (CORS) have been deployed around the world to support high accuracy positioning applications. CORS may be operated as an individual station, typically as the base station for GPS baseline surveying. However, in most cases nowadays, CORS are operated as a permanent *network*, providing opportunities to enhance the functionality of these reference stations in many aspects of operations (see Marel, 1998). A good example is the global network of the International GNSS Service (IGS) and their products (IGS, 2005). Figure 1.4 shows the location of many of the reference stations that make up the IGS network. Note that there are comparatively few IGS stations in the low latitude region. Recently the establishment of a few CORS in the Equatorial region has offered the opportunity to research the atmospheric effects on GPS in this area. These CORS are typically part of independent regional GPS networks with baseline lengths up to hundreds of kilometres. Combined with the IGS stations, the regional network can supply valuable GPS data to be analysed, and therefore contribute to greater understanding of the behaviour of the low latitude atmosphere.

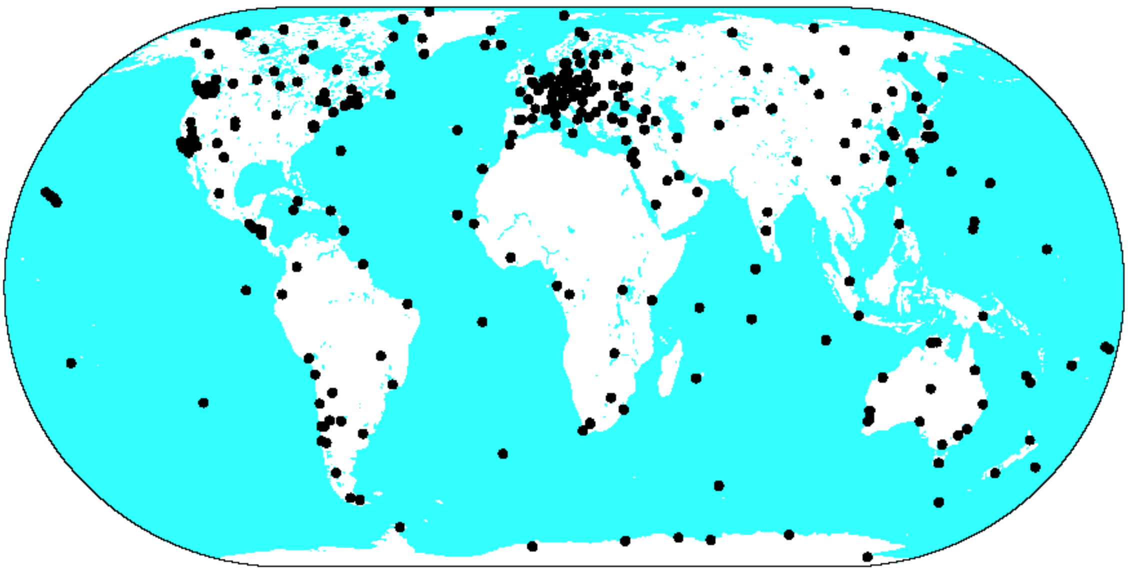

Figure 1.4 The IGS tracking stations (sourced from: http://igscb.jpl.nasa.gov/network/netindex.html).

1.1.2 The Local CORS & Network-Based Positioning

The shortcoming of IGS and regional networks is that their coverage is not dense enough to be sensitive to small-scale errors, and therefore they do not meet the requirements for GPS surveying in the area. At present, many countries have developed their own local GPS networks that extend over tens of kilometres. Carrier phase-based positioning by combining and interpolating (or extrapolating) measurements from a local network of reference stations is often referred to as "network-based positioning".

Figure 1.5 illustrates the benefits of using the network-based positioning approach.

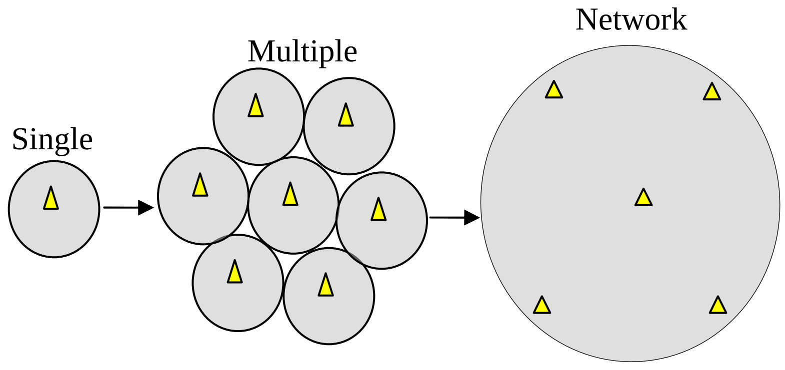

Figure 1.5 From single to multiple reference stations and from single-base to network-based positioning.

The single-base reference station approach provides a coverage of 10km or less for carrier phase-based positioning – related to the effectiveness of cancelling the spatially correlated errors using double-differencing techniques - in particular the atmospheric delay and GPS satellite orbital errors are distance-dependent (i.e. increase with the baseline length) (Beutler et al., 1988; Georgidaou & Kleusberg, 1988). Although a priori models and data differencing mitigate the errors, the *residuals* still distance-dependent. On the other hand, multiple reference stations cover a larger area because network-based positioning can model, to a greater or lesser extent, the *distance-dependent residual errors*.

The concept of carrier phase-based network-based positioning is very similar to so-called 'wide area' differential GPS (WADGPS), in a sense that both techniques generate 'network corrections' to a user's measurements. WADGPS provides regional coverage by utilising pseudorange code-based corrections to deliver the metre-level relative accuracy. On the other hand, the network-based positioning is an efficient way of improving long-range ambiguity resolution (AR), when reference station separations are many tens of kilometres, which is a key step for centimetre-level positioning (Han & Rizos, 1996a; Racquet, 1998; Wanninger, 1995; Wübenna et al., 1996). Network-based positioning may be implemented in static, rapid-static and kinematic positioning modes, and in (near) real-time or post mission operational modes.

Although research on network-based positioning algorithms has been underway over the last decade, and some commercially available network processing products, there is still room for improvements. One can partition the 'network corrections' into *dispersive* (ionosphere-related) and *non-dispersive* (troposphere- and orbit-related) components according to their dependency on the GPS signal frequencies. The dispersive and non-dispersive correction components exhibit different variations. By understanding the behaviour of distance-dependent errors (e.g. from residuals analysis), appropriate modelling can improve the quality of the corrections. Moreover, dispersive and/or non-dispersive corrections can be applied to various GPS measurement combinations, and hence benefit the user processing in many ways. This option is not available if 'lumped' (i.e. combined dispersive + non-dispersive) corrections are used.

Unlike the case of the functional model for network-based positioning, research on the associated stochastic models is still in its infancy. Even for the single-base reference positioning technique discussions in the research literature on the stochastic properties of GPS measurements are comparatively limited. Such stochastic models could be adopted, as a starting point, to aid in understanding the stochastic properties of network-based positioning. It is also desirable to find out whether applying such sophisticated stochastic models does improve the positioning process, and the quality of the results of network-based positioning.

1.2 Research Statements & Objectives

Atmospheric delay is very important accuracy limiting factor in GPS carrier phase-based positioning and low latitude areas are regions of strong atmospheric conditions. Atmospheric delay is a distance-dependent error in differential carrier phase-based positioning. Although it can be reduced somewhat by applying an a priori model, there remain considerable distance-dependent residual errors. Distance-dependent residual errors can be spatially modelled by carrier phase network-based positioning techniques.

The objectives of this research are therefore:

- To analyse the distance-dependent residual errors on GPS baselines in low latitude regions,

- To investigate the residual tropospheric delay on GPS baselines in low latitude regions,
- To develop a processing strategy for network-based positioning that can account for the distance-dependent residual errors, and
- To investigate the stochastic modelling for static network-based positioning.

The analysis of distance-dependent residual errors is essential in a sense that it provides the general background to the whole study. Since the distance-dependent residual errors vary spatially and temporally, they have been intensively studied by many investigators (Alves et al., 2006; Chen, 2001; Dai, 2002; Vollath et al., 2003; Wanninger, 1993; Wübenna et al., 1996). Moreover, the analysis will provide the basic knowledge for subsequent attempts to model the distance-dependent residual errors. The analysis for the effect of distance-dependent residual errors on GPS baselines was first conducted with some theoretical experiments. Next, the analysis of time-series of double-differenced residuals on three baselines in a low latitude region was conducted.

The investigation into the effects of regional tropospheric delay on GPS baselines was conducted using a network of CORS in South-East Asia. Since these CORS produce dual-frequency measurements, the linear combination of L1 and L2 can produce the 'Ionosphere-Free' (IF) observables. By using the precise GPS orbits during processing, the residuals of the IF combination are assumed to be dominated by the tropospheric delay. The investigation includes a performance analysis of a priori troposphere models and the effect of residual tropospheric delay on GPS station coordinates during the monsoon and inter-monsoon seasons. Additionally, the estimation of troposphere zenith path delay (ZPD) is conducted using the regional and local GPS network during the monsoon period.

A processing strategy for network-based positioning is proposed that uses the IF measurement combination and an existing network-based algorithm known as Linear Combination Method (LCM). The 'smooth' non-dispersive network correction is used to improve the residuals of the IF combination, and therefore indirect ambiguity for GPS L1 and/or L2 measurements can be resolved via various inter-frequency combinations such as the widelane and the narrowlane observables. Once the indirect

L1 ambiguity is resolved it can be removed from the original (double-differenced) L1 measurements. Finally, the dispersive and non-dispersive corrections can be applied in the positioning step. Data from CORS networks in mid-latitude and low-latitude areas were tested. The proposed processing strategy was tested in post-mission mode, but could be considered a ‘simulated’ real-time kinematic (RTK) mode.

The investigation into stochastic modelling for static network-based positioning was conducted by the variance-covariance estimation technique known as Minimum Norm Quadratic Unbiased Estimation (MINQUE). MINQUE uses the least squares residuals as the indicator with the assumption that it contains sufficient information to reflect the presence of the (residual) biases and measurement noises. In addition, the stochastic model can be applied in a two-stage process to transform the measurements into a set of new observables which should be free of temporal correlation. Tests were conducted using various GPS CORS networks.

1.3 The Research Scope

The experiments in this research were conducted using data from several CORS networks. The main reason for using such a data source is to assume that the station-dependent errors, such as hardware-related errors, multipath, and measurement noises, are at a minimum. This assumption is reasonable because CORS usually have a good positioning environment, geodetic-quality receivers are used, the antennas are robust against multipath, and an open sky view is guaranteed.

Although the main focus is the low latitude region, GPS data from mid-latitude sites were also tested.

Since the tests of network-based positioning are conducted in a simulated RTK mode, problems could occur if the user receiver does not remain stationery for a sufficient period of time for initialising the RTK process. The main reason is that the assumption of minimal station-dependent errors is no longer true. The station-dependent errors influence AR, even though distance-dependent errors can be reduced by the network-based positioning technique.

1.4 Contributions of the Research

The contributions of this research can be summarised as follows:

1) Analysis of distance-dependent residual errors in a low-latitude region has been carried out.

2) A comprehensive analysis of the regional tropospheric delay has been carried out in the South-East Asia area.

3) A new processing strategy for user network-based positioning has been developed based on the residuals after the IF measurements and network-based algorithm are applied.

4) A 'realistic' stochastic model has been adapted to the static network-based positioning.

1.5 Outline of Thesis

This chapter provides a background on the low latitude atmosphere, and argues why the Equatorial area should be a focus for Earth's atmospheric study in order to enhance the GPS positioning quality. Motivation, objectives, and the contributing factors for this research work are outlined.

Chapter 2 reviews some of the important concepts and topics that are frequently referred to and discussed in this research. There are four major issues: 1) background information about the GPS signals and mathematical modelling of the satellite-receiver ranges, 2) GPS signal propagation through the atmosphere, and its effect in general, and appropriate mathematical models to deal with it, 3) techniques of GPS positioning, and

4) details about relevant processing aspects of relative GPS positioning.

Chapter 3 discusses the effect and the residual analysis of distance-dependent errors on GPS baselines, and introduces the concept of long range AR. The basis for long range AR is explained via various GPS artificial measurements.

Chapter 4 presents some case studies of the effect of regional tropospheric delay in the South-East Asia area on GPS positioning. The performance of a priori tropospheric models and the precision of station coordinates are addressed using GPS data collected during monsoon and inter-monsoon seasons. Issues such as the estimation of ZPD using regional and 'local' GPS CORS network data during the monsoon season are discussed as well.

Chapter 5 presents background to network-based positioning, and the conventional network-based algorithm that is used in the study, followed by a new proposal for a network-based processing strategy. Tests were conducted for two CORS networks, one located in a mid-latitude region and the other in a low latitude region.

Chapter 6 presents background to the quality indicators that are often used in the 'realistic' stochastic model. The mathematical background of variance-covariance estimation by MINQUE is highlighted and adapted to the network-based positioning technique. The extension of the conventional stochastic model into a two-stage process is discussed in order to permit the handling of the temporal correlation of GPS measurements.

Chapter 7 summarises the research findings, draws some conclusions, and suggests recommendations for future research.

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ACADEMIC ACTIVITY

LIST OF PUBLICATIONS

(2003-Current):

Musa, T.A., Wang, J., Rizos, C. (2003): *Stochastic modelling for network-based GPS positioning*. Proc. of 6th Int. Symp. on Satellite Navigation Technology Including Mobile Positioning & Location Services, Melbourne, Australia, 22-25 July, *paper reviewed conference*.

Rizos, C., Kinlyside, D., Yan, T., Omar, S., & **Musa, T.A.** (2003): *Implementing network RTK: The SydNET CORS infrastructure*. Proc. of 6th Int. Symp. on Satellite Navigation Technology Including Mobile Positioning & Location Services, Melbourne, Australia, 22-25 July, *paper reviewed conference*.

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Musa, T.A., Lim, S., Rizos, C. (2005): *Modelling of Dispersive and Non-dispersive Effects on Network-Based Positioning*. Dynamic Planet 2005, Cairns, Australia, 22-26 August.

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***Musa, T.A**., Lim, S., Rizos, C. (2006). Network-based RTK Positioning: Impact of Separating Dispersive and Non-dispersive Components on User-side Processing Strategy. **Submitted to GPS Solutions*.

LIST OF PRESENTATIONS

By author (2003-Current):

Musa, T.A. (2003): *Stochastic modelling for network-based GPS positioning*. SNAP seminar, UNSW, Sydney, 20 June. *Oral Presentation*.

Musa, T.A., Wang, J., Rizos, C. (2003): *Stochastic modelling for network-based GPS positioning*. The 6th Int. Symp. on Satellite Navigation Technology Including Mobile Positioning & Location Services, Melbourne, 22-25 July. *Oral Presentation*.

Musa, T.A. (2003): *Stochastic Modelling for Network-Based Positioning*. The 30th Annual Research Seminars, School of Surveying & SIS, UNSW, Sydney, 10-11 November. *Oral Presentation*.

Musa, T.A. (2004): *A stochastic modelling method for network-based GPS positioning*. SNAP seminar, UNSW, Sydney, 18 June. *Oral Presentation*.

Musa, T.A., Wang, J., Rizos, C., Lee, Y.J., Mohamed, A. (2004): *Mitigating residual tropospheric delay to improve users network-based positioning*. The Int. Symp. on GPS/GNSS, Sydney, 6-8 Dec. *Oral & Poster Presentation*.

Musa, T.A. (2005): *Modelling of Non-dispersive Effects on Network-Based Positioning*. Staff-Student Development Seminars (SSDS), UNSW, Sydney, 7 July. *Oral Presentation*.

Musa, T.A. (2005): *GPS Network-Based Approach to Mitigate Residual Tropospheric Delay in Low Latitude Area*. Staff-Student Development Seminars (SSDS), UNSW, Sydney, 28 September. *Oral Presentation*.

Musa T.A. (2005): *Modelling of dispersive and non-dispersive effects on network-based positioning - user processing perspective*. The 32nd Annual Research

Seminars, School of Surveying & SIS, UNSW, Sydney, 7-8 November. *Oral Presentation.*

By co-author:

Musa, T.A., **Wang, J.**, Rizos, C. (2004): *A stochastic modelling method for network-based GPS positioning*. GNSS2004, Rotterdam, The Netherlands, 16-19 May. *Oral Presentation.*

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Musa, T.A., Lim, S., **Rizos, C.** (2005): *Low latitude troposphere: A preliminary study using GPS CORS data in South East Asia*. U.S. Institute of Navigation National Tech. Meeting, San Diego, California, 24-26 January. *Oral Presentation.*

Musa, T.A., **Lim, S**., Rizos, C. (2005): *Network-Based Approach to Mitigate Residual Troposheric Delay In Low Latitude Area*. Research Seminar, School of Mechanical & Aerospace Engineering, Seoul National University, Korea, 30 March. *Oral Presentation.*

Musa, T.A., Lim, S., & Rizos, C. (2005). Presented by : **Andrew G. Dempster**: *GPS network-based approach to mitigate residual tropospheric delay in low latitude area*. 18th Int. Tech. Meeting of the Satellite Division of the U.S. Institute of Navigation, Long Beach, California, 13-16 September. *Oral Presentation.*

Musa, T.A., Lim, S., Yan, T, **Rizos, C.** (2006). Mitigation of Distance-Dependent Errors for GPS Network Positioning. *International Global Navigation Satellite Systems Society,* Holiday Inn Surfers Paradise, Australia, 17-21 July.

LIST OF COURSE & WORKSHOP ATTENDED

Workshop: ***Research Devp. Program Induction Workshop & Group Presentation***
Presenter: Dianne Wiley (UNSW)
Location & date: UNSW, NSW, Australia, 23 - 24 June 2003.

Workshop: ***Real-Time Kinematic Positioning***
Presenter: Prof. Will Featherstone, Western Australian Center for Geodesy, Curtin University
Location & date: UNSW, NSW, Australia, 5 December 2004.

Workshop: ***GNSS Developments and the Land Surveyor***
Presenter: Prof. C. Rizos, Craig Roberts, Thomas Yan, School of Surveying & SIS, UNSW
Location & date: UNSW, NSW, Australia, 6 - 10 December 2004.

Short Course: ***An Introduction to Precise Point Positioning***
Presenter: Prof. Yang Gao, Dept of Geomatics Eng, The University of Calgary, Canada
Location & date: UNSW, NSW, Australia, 15 December 2004.

Short Course: ***Advanced RTK-GPS: Concepts & Operations***
Presenter: Prof. C. Rizos, Dr Craig Roberts, Thomas Yan, School of Surveying & SIS, UNSW
Location & date: UNSW, NSW, Australia, 7 - 8 February 2005.